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Bangladesh's dynamic coastal regions and sea-level rise

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ABSTRACT

The physical geography of Bangladesh's coastal area is more diverse and dynamic than is generally recognised. Failure to recognise this has led to serious misconceptions about the potential impacts of a rising sea-level on Bangladesh with global warming. This situation has been aggravated by accounts giving incorrect information on current rates of coastal erosion and land subsidence. This paper describes physical conditions within individual physiographic regions in Bangladesh's coastal area based on ground-surveyed information, and it reviews possible area-specific mitigation measures to counter predicted rates of sea-level rise in the 21st century. Two important conclusions are drawn: the adoption of appropriate measures based on knowledge of the physical geography of potentially-affected areas could significantly reduce the currently-predicted displacement of many millions of people; and the impacts of a slowly-rising sea-level are currently much less than those generated by rapidly increasing population pressure on Bangladesh's available land and water resources and by exposure to existing environmental hazards, and the latter problems need priority attention.

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Introduction

There is a widespread misconception that a rising sea-level with global warming will overwhelm Bangladesh's coastal area contour by contour and will thereby displace as many as 10–30 million people in the 21st century e.g., (Gore, 2009; Houghton, 2009). In some accounts, that situation will be aggravated by high rates of land subsidence (Syvitski et al., 2009), a recent doubling of the rate of sea-level rise (Smith, 2012) and rapid, on-going rates of coastal erosion (Vidal, 2013a,b). The accounts given to-date imply that the Bangladeshi people are helpless against a rising sea-level and will be unable to resist the rising water.

Those assumptions and descriptions are incorrect. Bangladesh's coastal area is not uniform, nor is it static. It is dynamic, and so are the people of Bangladesh. Environmental scientists have an important role to play in establishing environmental facts in order to identify practical, area-specific, mitigation measures to counter realistically-probable impacts of sea-level rise in different geographical regions. This account illustrates the kinds of information on geomorphology, hydrology, soils, land use and socio-economic geography that are needed to provide a sound basis for planning area-specific measures to counter sea-level rise in low-lying coastal areas elsewhere in the world.

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The geographical setting

Regional diversity

Soil surveys carried out of the whole of East Pakistan and Bangladesh between 1963 and 1975 showed that the country has a great diversity of physiographic regions and that relief, soil and hydrological patterns within regions are often complex (Brammer, 2012). This diversity and complexity is clearly visible on satellite images. All or parts of four physiographic regions adjoin the coast (E, J, L, M), three of them divided into subregions (Fig. 1); low-lying parts of four regions further inland (D, F, I, J) lie sufficiently close to the coast that they could be affected by a rising sea-level at an early date. As is described below, land accretion and erosion are taking place at different rates along the coast, and the natural physical environments in each of the regions have been changed in various ways by human interventions, particularly by embankments built to prevent flooding by saline tidal water or seasonal river floods. The coastal zone is exposed to the risk of tropical cyclones in the pre-monsoon and post-monsoon seasons, with the associated risk of storm surges in areas close to the coast.

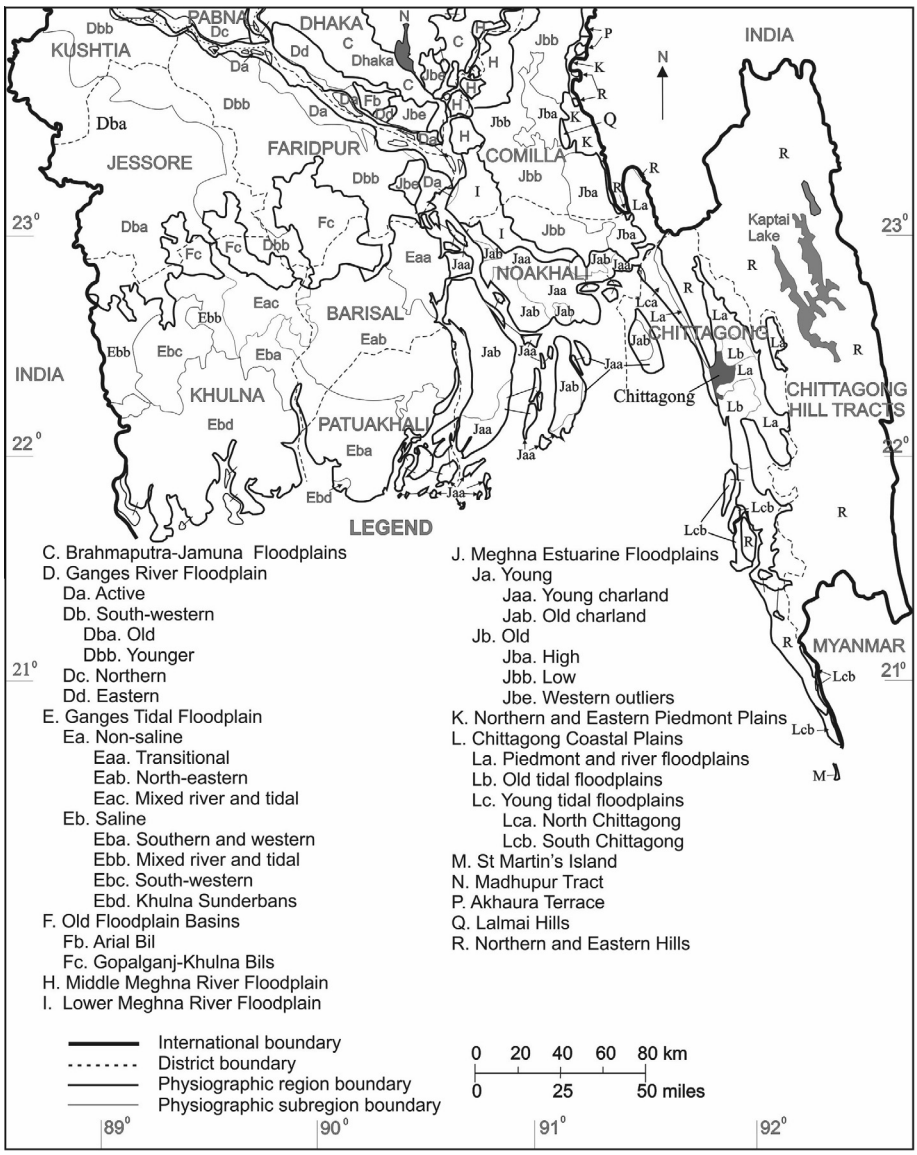

Fig. 1. Physiographic regions in southern Bangladesh. Source adapted from Brammer, 2012.

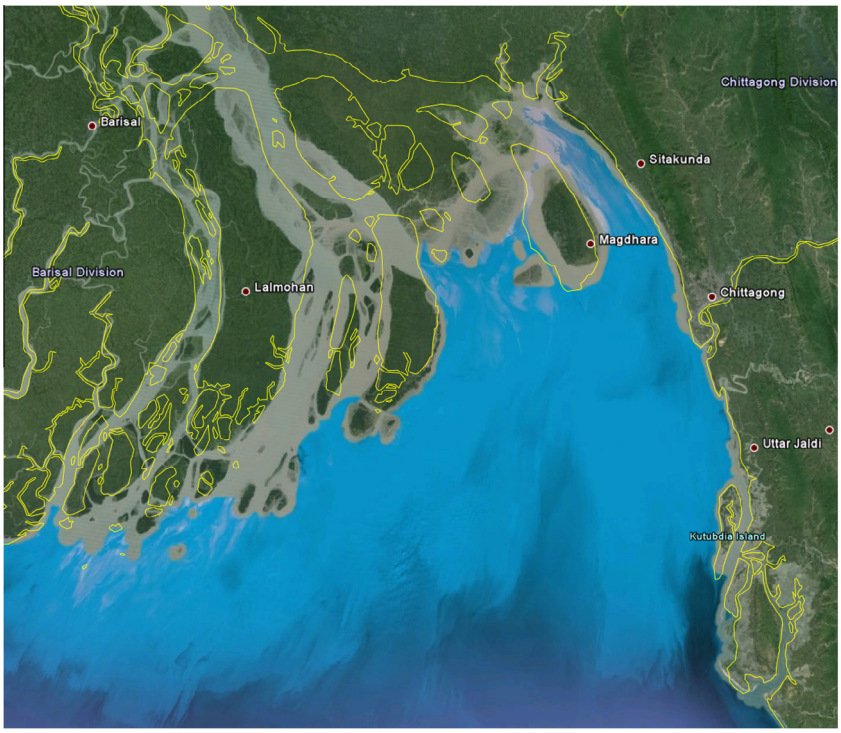

Fig. 2. Google Earth image of the Meghna estuary.

Coastal changes

Rapid geomorphological changes are taking place in the Meghna estuary (Subregions Jaa, Jab). The Google Earth image in Fig. 2 shows the 1943 land boundaries superimposed on the 2013 land boundaries[2]. Comparison of Landsat images taken in 1984 and 2007 showed a net land gain of 451 km^2 in the Meghna estuary within that period, representing an average annual growth rate of 19.6 km^2 (Fig. 3) Brammer, in press. Earlier, Allison (1998) had calculated annual net gains of 14.8 km^2 between 1792 and 1840 and of 4.4 km^2 between 1840 and 1984. This historical evidence of large-scale net annual land gains in the Meghna estuary suggests that land gain might exceed land loss resulting from the slow rates of sea-level rise projected for the 21st century. That would be especially likely if predicted increases in monsoon rainfall increased run-off and river sediment loads in the Brahmaputra–Ganges–Meghna (GBM) catchment area; and new land could also be added by continued land reclamation in the north-east of Subregion Ja by constructing cross-dams to link new islands with the mainland (de Wilde, 2011). On the other hand, accretion rates could be reduced if future dam construction in the Ganges–Brahmaputra–Meghna catchment area reduced river sediment loads significantly.

Figs. 2 and 3 show that, although there was a net gain of land, there were also considerable land losses in the Meghna estuary. For instance, about 40% of Sandwip island in the east was eroded, (not the 90% reported by Vidal (2013a)), and there were considerable losses in the north of Hatia, north-east of Bhola and the south-west of the former Ramgati island. Beyond the estuary, rates of coastal change are small or undetectable. On the south-western coast (Region E), there have been small amounts of erosion locally, with amounts generally increasing westward towards the Hooghly estuary in India (Fig. 3); Allison (1998) made similar observations. These rates are much less than the dramatic erosion rate of 200 m a year reported by Vidal (2013b) in the Sunderbans area (in and adjoining Subregion Ed in Fig. 1). In the south-east, changes are generally small or undetectable on the coast of the Chittagong Coastal Plains (Region L), except in the south of Kutubdia island which lost approximately 10% of its previous area, (not the 50% reported by Vidal (2013a)). The exaggerated reports by Vidal – based in the first case on selective reporting from a technical study of the Sunderbans using satellite image analysis unsupported by ground-truthing, and in the second case on unchecked accounts by displaced persons – are quoted here because they provide examples of situations where scientists can themselves check exaggerated media reports of coastal changes in

[2] The Bangladesh map outline on the Google Earth image is based on the 1:500,000 Barisal map sheet produced by the Army Map Service (RMLD), Corps of Engineers, US Army, Washington D.C., 1955, based on Survey of India 1-inch sheets dated 1909-42 and ½-inch sheet dated 1927, and USHO sheet 6170 1948, with planimetric detail revised by photo-planimetric methods. The date of the airphotos used is not stated on the map, but it is thought to be 1943. At that time, the main Meghna channel flowed West-East across the north of the estuary. This channel was rapidly infilled with sediments following the 1950 Assam earthquake which brought huge sediment loads into the Brahmaputra river, the fine material of which was quickly carried down to the estuary Brammer (2012).

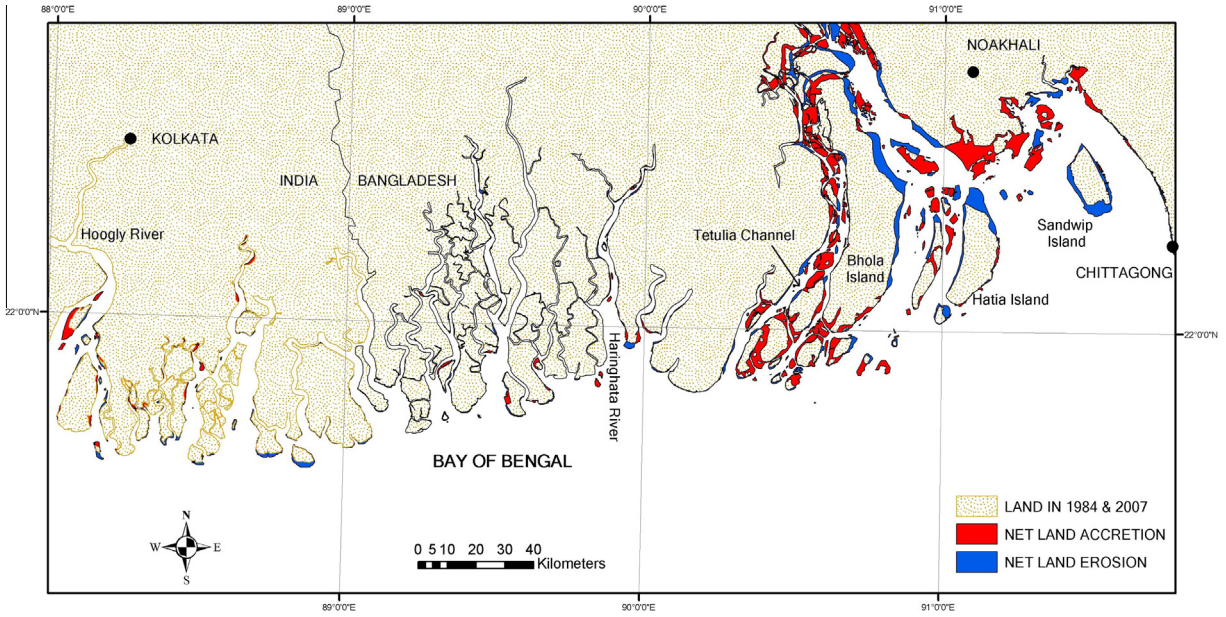

Fig. 3. Gains and losses of land on the Brahmaputra–Ganges–Meghna delta front 1984–2007.

Bangladesh by examining Google Earth satellite images which (at present, at least) give 1943 land boundaries as a reference base.

The Meghna estuary is an unstable area for settlement, and it is badly exposed to cyclones and storm surges; the megacyclone in November 1970 killed an estimated 300,000–500,000 people[3]. Newly-formed land is less suitable for settlement and agriculture than older land eroded because of the raw state and salinity of new alluvium and continuing exposure to tidal and storm surge flooding, together with lack of fresh water for domestic use. Prevention of land erosion is likely to be impractical against the force of flood and ebb-tide currents in estuarine channels, except possibly locally by closing off minor channels.

Changes on land

Unlike much of Subregion Ja, the Ganges Tidal Floodplain (Region E) is mainly a stable land area. It is crossed by innumerable tidal rivers and creeks (Fig. 4) bounded by low, narrow levees with silty sediments which surround basins with heavy clay soils. Under natural conditions, the land was flooded at high tides, either throughout the year, at high Spring tides or only in the monsoon season when rivers entering the region from inland ran at high levels. Tidal flooding was by saline water throughout the year in the extreme south-west, but only in the dry season in the north-west and near the south-eastern coast (Fig. 5). Mean annual rainfall ranges between 1750 mm in the north-west and >3000 mm in the south-east.

As is shown in the legend for Fig. 1, the subregions within Region E differentiate a wide range of environments. The major subregions Ea and Eb respectively differentiate areas where soils are non-saline and saline in the dry season; further subregions differentiate a transitional area between tidal and river floodplain landscapes in the north-east (Eaa), areas of mixed river and tidal sediments in the north-centre and north-west (Eac, Ebb), an area with extremely acid soils (Acid Sulphate Soils) in the south-west (Ebc), and the Sunderbans mangrove forest (Ebd). This region is exposed to cyclones and accompanying storm surges; the latter can extend far inland along the tidal rivers, as they did in cyclone Sidr in 2007 and cyclonic storm Aila in 2009.

Except in the transitional north-eastern subregion and in the Sunderbans forest, most of Region E was empoldered by embankments built alongside the main rivers in the late-1950s and 1960s to prevent tidal flooding. Sluices were provided in the embankments to drain accumulated rainwater at low tide. Topsoils in embanked areas in the south and south-west are saline only in the dry season; monsoon-season rainfall is sufficient to wash out salt accumulating by capillary rise to the surface from saline groundwater in the dry season, enabling rice to be grown in the monsoon season; in freshwater areas, over the extensive areas where rivers remain non-saline, an additional rice crop can be grown with irrigation in the dry season. Broadly similar conditions occur in coastal parts of Subregions Lb and Lc on the Chittagong Coastal Plains except that the mainland part of Subregion Lcb is mainly used for salt production.

[3] Range of estimates by government and NGOs. The uncertainty arose because of the widespread loss of local government records and the lack of information on the number of migrant labourers in the coastal area for the main *aman* rice harvest at the time of the disaster. The author was with the UN in East Pakistan at the time.

Fig. 4. Satellite image of parts of the Sunderbans forest and adjoining cultivated land on the Ganges Tidal Floodplain.

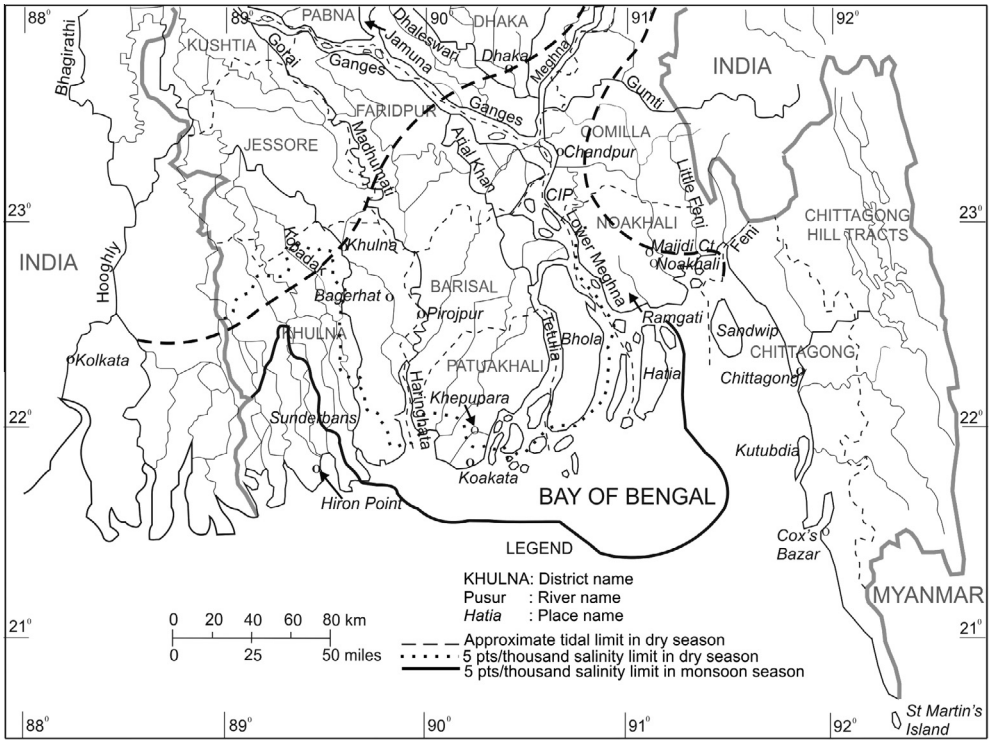

Fig. 5. Seasonal salinity limits, tidal limit and places named in the text. Source: CEGIS.

Environmental conditions have not remained static since the major embankments were built. Confinement of the rivers between embankments caused siltation of some rivers in the north-west of Region E which, in turn, blocked drainage from adjoining polders, causing them to be perennially flooded or waterlogged (visible on satellite images). Additionally, dry-season flow in the Gorai-Madhumati, the main river carrying fresh water into western parts of the region, has decreased over time. That was mainly due to reduced flow from the Ganges river into the Gorai following construction of the Farakka barrage across the Ganges in India in 1975, but abstraction of river water and groundwater for dry-season irrigation on the Ganges River Floodplain (Region D) through which the Gorai-Madhumati passes has also reduced river flow

(Brammer, in press). Extreme western parts of Regions D and E lie in the moribund Ganges delta where rivers have been cut off from the Ganges for several centuries, making conditions in the west of Region E naturally saline in the dry season.

The progressive inland movement of the dry-season salt-water limit in south-western rivers has had adverse impacts on soil salinity, crop production and availability of potable domestic water supplies in affected areas. Measurement of progressive changes is made difficult by variations in rainfall between years, with knock-on effects on river flow and leaching/accumulation of salt in soils; by the occasional impacts of catastrophic events such as cyclones and storm surges, the latter of which can breach embankments and expose land to saline flooding and sedimentation again until embankments and sluices are repaired; and by local breaching of embankments for brackish-water shrimp farming which has expanded greatly in recent decades and which negates the crop-protection purpose for which the embankments were originally provided.

Land subsidence

An additional dynamic factor in Region E is land subsidence. Under natural conditions, such subsidence was counteracted by sedimentation from the rivers at high tide. The construction of embankments cut off this natural sediment accretion within polders. Few studies have been made to-date to measure actual subsidence rates or determine its causes, and the situation is complicated by the breaching of embankments in some areas for shrimp farming and by storm surges which periodically enable new (but probably irregular) sedimentation on the land.

Using high-resolution satellite altimetric data unsupported by ground truthing, Syvitski et al. (2009) included the Ganges delta – with a stated rate of 18 mm/year – among 33 'sinking deltas' world-wide, grouping it with deltas experiencing large subsidence rates attributed to human activities such as embankment construction and water or gas abstraction. This assertion is incorrect on several grounds. The Ganges delta also includes the Ganges River Floodplain (Region D), not just the tidal floodplain (Region E) assumed by the authors; as is described below, there is no field evidence that either of these regions is subsiding at such a very high rate; and subsidence rates are not uniform within the area as implied by the single figure of 18 mm/year given by the authors.

Measurements of plinth levels of a 15th century mosque at Bagerhat in the north of the tidal floodplain (Fig. 6), a 400-year-old Hindu temple in the Sunderbans forest in the south and a 200-year-old temple 25 km north-east of Khepupara in the south-east show that long-term subsidence rates in those areas have not exceeded 1–2.5 mm/year (Sarker et al., 2012); (places named are shown on Fig. 5). If subsidence had occurred at the 18 mm/year rate given by Syvitski et al., these buildings would now be 2.4–7.6 m below sea-level. Calculation of depths to radio-carbon-dated organic materials in the region (mainly in the Sunderbans mangrove forest where embankments have not interfered with sedimentation) show subsidence rates of 1.3–7.1 mm/year (Table 1), from which probably 1.3 mm/year can be subtracted for global sea-level rise (see below); dating of exposed 300-year-old salt kilns on the coast in the east of the Sunderbans about 35 km west of Kuakata suggests subsidence rates in that area of 5.2 ± 1.1 mm/year (Hanebuth et al., 2013); and measurements in neighbouring West Bengal gave changes ranging between uplift of 2 mm/year north of Calcutta (now Kolkata) and subsidence of ~5 mm/year in the south of the Indian Sunderbans (Stanley and Hait, 2000). Therefore, the balance of available evidence suggests that most of the region is currently subsiding at less than 2 mm/year except near the coast where rates may be up to ca 6 mm/year.

Subsidence in Region E is not caused by gas abstraction, and only to a limited extent by groundwater abstraction in the few urban areas such as Khulna in the north. Much of the Ganges delta is underlain by Holocene, Pleistocene and Tertiary

Fig. 6. Fifteenth century Sunakhola mosque, Bagerhat.

Table 1
Land subsidence rates on the Ganges Tidal Floodplain calculated from radio-carbon-dated buried organic material.

Site No.	Material	Depth (m)	Radio carbon age	Calendar age (years BP)	Depth/calendar age (mm/year)
6BP48	Buried tree	1.5	455 ± 45	614 ± 14	2.4
19BS98	Marine shell	1.4	1200 ± 30	730 ± 50	1.9
7BS99	Wood	0.7	90 ± 40	227 ± 48	3.1
7BS99	Crab claw	2.2	127 ± 7	309 ± 8	7.1
12BS99	Peat	1.5	570 ± 50	584 ± 64	2.6
BVS16	Peat	1.1	910 ± 50	820 ± 111	1.3
12BS99	Peat	3.2	2300 ± 40	2378 ± 29	1.3
12BS99	Peat	5.8	2690 ± 40	3192 ± 17	1.8

Notes: 1. Data in columns 1–5 from Allison et al. (2003), Table 1. That table includes coordinates of the sites sampled.
2. Column 6: depth (col. 3) divided by calibrated calendar age (col. 5) = annual change in land levels relative to mean sea-level.

sandy sediments that are not subject to compaction with water abstraction; and Holocene peat layers underlying large parts of the tidal floodplain have remained saturated since their formation and so have not shrunk by drying out (except locally where water has been abstracted under Khulna city). It seems probable that most of such subsidence as is occurring is due to tectonic subsidence of the Bengal Basin within which the region lies, possibly complicated by folds and faults within the basin (Stanley and Hait, 2000; Steckler et al., 2008).

Elsewhere, large areas were reported to have subsided in Noakhali District (in the south-west of Subregion Jb) and south of Chittagong (in Region L) in the 1762 Arakan earthquake (Khan, 1977; Cummins, 2007).

Sea-level rise

Tide-gauge records

Long-term, global, tide-gauge records show that changes in sea-level occurred throughout the 20th century (Smith, 2012). Analysis of data for stations in the north of the Indian Ocean with >40 years of records up to 2004 showed rates of rise of 1.06–1.75 mm/year, with a regional average of 1.29 mm/year (Unnikrishnan and Shankar, 2007). The latter authors attributed the considerable inter-annual variation found at all stations to variations in the force of onshore winds in the monsoon season, inflow of fresh water from major rivers and water salinity. Fig. 7 shows the inter-annual variations and overall trends at Diamond Harbour (Calcutta), Hiron Point, Khepupara and Cox's Bazar[4]. They attributed the differences between their adjusted rate of 5.74 mm/year at Diamond Harbour (Calcutta) and the average rate of 1.29 mm/year in the Indian Ocean to land subsidence.

In 2007, Unnikrishnan and Shankar considered the period since collection of satellite altimetric data commenced in 1993 to be too short for estimating long-term trends. However, based on satellite data, Allison et al. (2009) gave a global estimate of 3.4 mm/year, and Smith (2012) stated that global sea-level rise had increased from its 130-year average rate of 1.7 mm/year to about 3 mm/year over the past 20 years. These rates are more than twice as high as those given by Unnikrishnan and Shankar for the north Indian Ocean, so further investigations were made to try to establish current rates affecting Bangladesh.

Examination of data from the Permanent Service for Mean Sea level (PSMSL) established that complete long-term tide-gauge data were not available for stations in the Bay of Bengal. Therefore PSMSL data were examined for a number of stations around the world with complete or near-complete, long-term records, from which seven widely-distributed stations were selected for comparison with the Kolkata Diamond Harbour site (Fig. 8). Running mean analyses were used instead of the regression analyses used in Fig. 7 in order to identify any changes in trends within the study period and also to isolate those trends from possible changes due to tectonic warping or isostatic rebound which, it was assumed, would be constant throughout the periods of record.

In fact, the running mean analysis for Diamond Harbour shows a marked trend change around 1975. That was the year when the Farakka barrage started to divert additional dry-season flow down the Bhagirathi into the Hooghly river; similar trend changes occurred at two gauge stations upstream from Kolkata (Garden Reach; Tribeni) (PSMSL). Elsewhere, the 18.6-year cyclical lunar tide fluctuations are apparent at Honolulu and some other stations. However, the analyses show no evidence that the rate of global sea-level rise has doubled in the past 20 years. This finding raises questions about the reliability of satellite data interpretations based on the limited number of years since their introduction.

Endangered interior regions

Immediately inland from the Meghna estuary and the Ganges Tidal Floodplain are five low-lying regions/subregions (D, Fc, I, Jbb, Jbe) that might be affected by a rising sea-level as early as the coastal regions. These regions/subregions include a

[4] The data for Khepupara are almost certainly too high by an order of magnitude, but it has not been possible to verify this. However, the 200-year-old temple 25 km north-east of that town referred to earlier remains above high tide level, and oxidised raised-beach sands at Koakata on the coast 25 km to the south, recognised on the soil survey of the area, lie above MSL. Khepupara is wrongly located on the PSMSL map. It actually lies at 21^0.59' N, 90^0.13'E: see Figure 5, which also shows the locations of the other stations referred to.

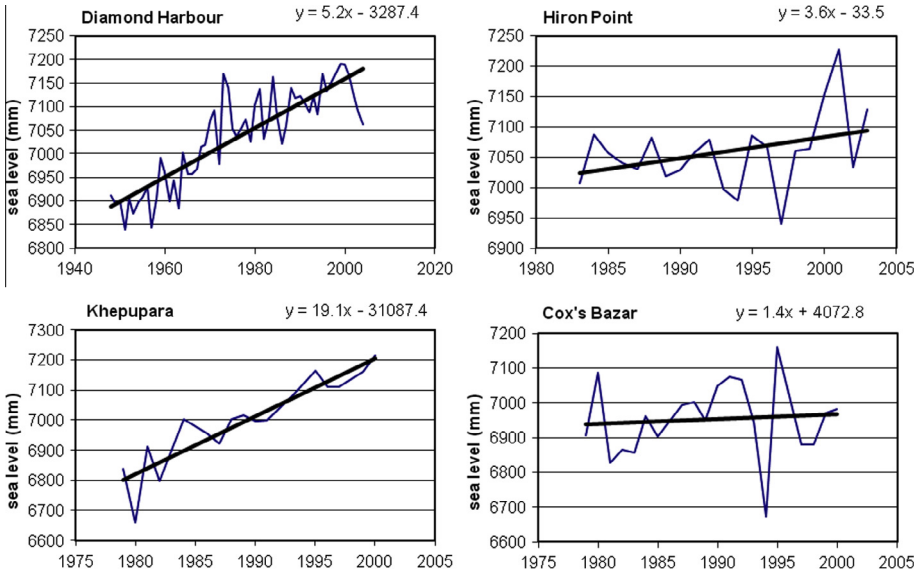

Fig. 7. Sea-level trends at four gauging stations in Bangladesh and West Bengal.

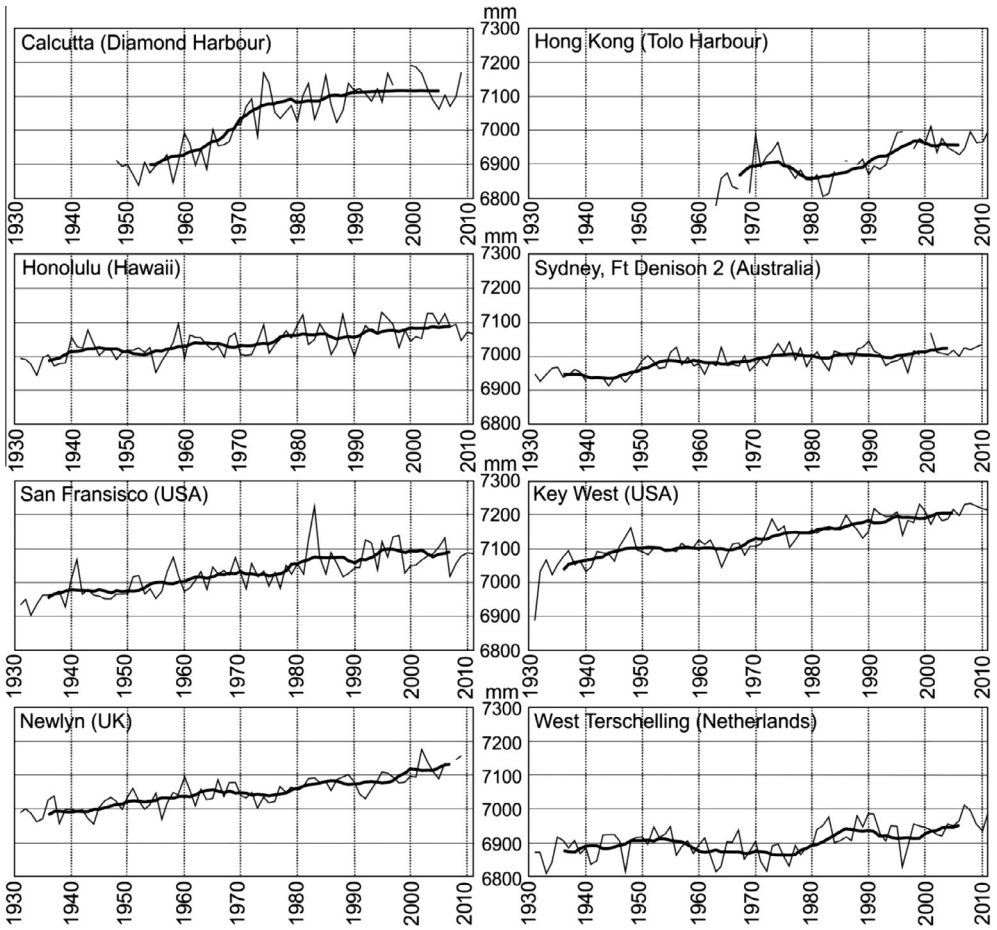

Fig. 8. Mean annual sea-level at selected tide gauge stations world-wide with ten-year running means. Notes: (1) Source: Permanent Service for Mean Sea Level (PSMSL). (2) Data missing: Calcutta 1997, 1998. Hong Kong 1968, 1985, 1987, 1997. Sydney 1941, 2000. Key West 1953. Newlyn 2007, 2010. (3) For missing years, dummies were inserted by taking the average of the two preceding and two following years.

wide diversity of environmental conditions that need to be taken into account in assessing potential impacts of sea-level rise and in considering appropriate mitigation measures.

Region I and Subregions Jbb and Jbe have predominantly deep silty soils on smooth relief with few rivers and creeks. Much of Region I lies within the Chandpur Irrigation Project (CIP) area that is embanked, drained by pumps and tidal sluices, and irrigated with water from the Lower Meghna river. Subregion Jbe and southern parts of Subregion Jbb are seasonally flooded 1–3 m deep by rainwater ponded on the land by high external river levels, so that they, too, do not receive annual increments of new alluvium that could maintain land levels to counteract a rising sea-level. The south-western part of Subregion Jbb stays wet for much or all of the dry season, partly due to subsidence – a large area is reported to have sunk in the 1762 Arakan earthquake (Khan, 1977) – and partly to blocking of drainage following the recent build-out of land in Subregion Ja shown in Fig. 2. Much of Region I and Subregion Jbb is irrigated and cropped throughout the year, and they are densely settled. A rising sea-level will increase seasonal flooding depths, extend the area that stays wet in the dry season and eventually endanger the CIP if saline water in the Lower Meghna river reaches the project headworks at Chandpur in the dry season. Embankments will need raising and strengthening against higher flood and storm-surge levels.

The southern part of Region D comprises an active floodplain (Subregion Dac) within and adjoining the main river channel and meander floodplains of two ages (Subregions Dba, Dbb). The active floodplain comprises new alluvial formations (*chars*) that are constantly being formed and eroded by shifting river channels; it is relatively sparsely settled. Meander floodplains have ridge and basin relief formed by levees and backswamps that were abandoned several centuries or longer ago, with 2–3 m elevation differences between seasonally shallowly-flooded ridge crests and adjoining deeply flooded basin centres. Calcareous, loamy soils on the ridges grade into heavy clay basin soils that have an acid upper layer over calcareous lower layers. Except close to river channels, seasonal flooding is by ponded rainwater (hence the acid topsoils, despite new alluvium being calcareous), and basin centres stay wet long into the dry season. Much of the land is irrigated and cropped throughout the year, and the area is densely settled, but less so than in Subregion Jbb. Areas close to the Lower Meghna river are exposed to cyclones and storm surges that affect the Meghna estuary. A rising sea-level would probably have little impact on the already unstable active floodplain, but it would increase seasonal flooding depths in Subregions Dba and Dbb and would perennially flood basin centres in their southern parts.

Subregion Fc comprises low-lying, enclosed basins with muck or peat at the surface in the basin centres and clay overlying peat on the basin margins. The basins are seasonally flooded 1–3 m deep by ponded rainwater and the raised groundwater-table (which is brackish in the south-west). Basin centres stay wet throughout the dry season and are under natural reed vegetation. Marginal areas are mainly cropped only in the dry season; higher areas are cropped throughout the year with dry-season irrigation. The subregion is relatively sparsely settled. A rising sea-level would increase the area of perennially-flooded land and might extend the area affected by brackish groundwater in the south-west.

Mitigation possibilities

Impacts and adaptation

The direct impacts of a rising sea-level will be to aggravate or accelerate some of the adverse effects of natural and human-induced environmental changes described in individual regions and subregions above: i.e., draw further inland the salt-water front in western parts of the Ganges Tidal Floodplain; and further impede drainage from interior areas east of the Lower Meghna river and from individual basins within regions west of that river. A rising sea-level could also increase rates of erosion of relatively older land on the major islands in the Meghna estuary, but this would be offset by continuing new land formation and reclamation elsewhere in the estuary. Ways to counteract adverse impacts need to be sought, tested and implemented where found practical.

The Bengali people have generations of experience of adapting to changing environmental conditions caused by shifting river channels, land creation and erosion, and the impacts of floods, cyclones and storm surges. Their traditional cropping patterns and practices were closely adapted to micro-scale differences in soil and hydrological conditions (Brammer, 2004). They continued to adapt during the period of rapid change since the 1950s when the first major flood embankments were constructed and, later, with the spread of dry-season irrigation and the introduction of high-yielding crop varieties. The country's government, too, has long experience of managing change, including measures to cope with recurrent natural disasters. Bangladesh is not helpless, therefore, against coping with sea-level rise, but it might need financial and technical assistance with providing practical mitigation measures.

Mitigation measures

In brief, twelve major kinds of intervention could be used to counter foreseen impacts of sea-level rise during the 21st century (described in more detail in Brammer (Brammer, in press). The Bangladesh Government's current mitigation plan (Government of Bangladesh, 2008) does not go into such detail, focusing mainly on impacts of climate change and referring briefly to the need to reinforce flood embankments.

1 Most urgently needed are ways to maintain freshwater flow to western parts of the Ganges Tidal Floodplain in order to prevent the salt-water front from moving further inland. Studies are needed to investigate the most practical way (or ways) to do this. The most direct method, already under investigation (Brammer, 2010), would be to divert additional water from the Ganges river down the Gorai-Madhumati river by means of a barrage across the Ganges in Bangladesh (which may need supplementation by diverting water into the Ganges from the Brahmaputra–Jamuna). Alternatively, possibilities must be examined to divert water to the south-west from the Ganges river downstream from the Ganges–Jamuna confluence or from the Arial Khan river. Such interventions are technically very difficult and costly on huge, sediment-laden rivers such as the Ganges and Jamuna with unstable channels and large differences in flow between the monsoon and dry seasons. The costs of providing and maintaining large-scale water diversions need to be weighed against the costs of providing alternative solutions to support the lives and livelihoods of the present and projected future populations in saline-affected areas of the south-west, including possibly their resettlement and employment outside the area.

2 The secondmost important measure needed is to find means to manage Coastal Embankment Project polders in ways that allow tidal water to enter them at appropriate times of the year in order to deposit sediment at sufficient rates to raise land levels in parallel with a rising sea-level and local land subsidence rates (a process known in England as 'warping'). Embankments will need to be raised and strengthened as sea-level rises. The Coastal Embankment Project will also require better management than in the past, including provision for the more speedy repair of embankments following damage by storm surges.

3 Where sediment accretion does not occur, as in regions/subregions flooded by rainwater, provide pump drainage (as is presently done in the Chandpur Irrigation Project area) to enable high-yielding crop production to continue in the monsoon season. Pump drainage might also be needed in parts of the Ganges Tidal Floodplain and the Chittagong Coastal Plains where warping is considered to be impractical or inadequate.

4 Either as an alternative to the latter or as a supplementary measure, make raised beds or platforms on which to grow appropriate crops. This is a measure that farmers are familiar with and might introduce themselves in advance of large-scale technical measures described in 2 and 3 above.

5 Practise fish farming (including shrimp farming) in perennially-flooded areas.

6 In the Meghna estuary, continue long-term land reclamation studies already initiated (de Wilde, 2011). Particularly needed now is research to develop methods for bringing new land formations under cultivation more quickly and to provide fresh water for domestic use (including making use of rainwater catchment: the area receives 2000−>3000 mm mean annual rainfall).

7 In rural areas, raise house plinth levels above the highest predicted storm-surge levels and increase cyclone shelter capacity as population grows. In urban areas, empolderment and pump drainage might be needed to protect existing built-up areas, and planning of future developments should take into account predicted levels of sea-level rise and storm-surge heights.

8 For Chittagong and Cox's Bazar, the two major coastal cities most exposed to sea-level rise and to storm surges, the creation of artificial raised land using material from neighbouring soft-rocked hills should be investigated for planning further expansion; (similar measures with imported material could safeguard property and lives on St Martin's Island, Region M). Existing buildings and infrastructure on floodplain land (including the airports) will need to be protected by reinforcement of existing embankments plus pump drainage. The practicality and costs of constructing barriers or locks on the Karnaphuli river to protect Chittagong port against existing levels of storm surges and future sea-level rise deserve investigation.

9 Reinforce flood management measures in inland regions – e.g., in and around Dhaka city – that become subject to higher and more frequent floods as water levels rise in the Lower Meghna river and estuary downstream.

10 In the longer term, investigate the practicality of diverting river flow and sediments from the main rivers to areas flooded by rainwater (such as Region I, and southern parts of Subregions Dbb and Jbb) so as to raise land levels in parallel with the rising river levels. Such a measure might be impractical for peat basins in Subregion Fc: making raised beds for cultivating high-value fruit and vegetables might be a practical mitigation measure for such areas together with fish farming in channels between the beds; and producing reeds for biofuel together with fish-farming might be possible in perennially-wet areas.

11 In the longer term, too, investigate the practicality of constructing barriers across river mouths in the south-west to prevent salt-water intrusion, as in The Netherlands. This would be a very costly and environmentally problematical intervention that might only be entertainable late in the 21st century if the measures recommended above for the Ganges Tidal Floodplain are by then becoming insufficient to prevent continuation of agricultural or fish production in the region. Preferably, any such barriers should be built on the inland margin of the Sunderbans forest; tidal sedimentation will probably continue to raise land levels within the forest with a rising sea-level.

12 Take measures to educate and train increasing numbers of people to find employment outside the coastal zone and to generate employment for them outside primary production. Exposure to cyclones and storm surges will continue to make this a hazardous area for settlement and economic activities; and poor communications make provision of government and commercial services difficult in large areas, especially in the Meghna estuary and in large parts of the Ganges Tidal Floodplain.

Conclusions

Bangladesh's exposure to the growing hazard of sea-level rise in the 21st century needs to be seen in the perspective of its exposure to current environmental hazards and its growing development needs. If sea-level is currently rising at 1.3 mm/year, that is by only 13 mm (= 0.5 inch) in 10 years. Even if the rate is 3 mm/year, that is by only 30 mm (=1.2 inches) in 10 years. But Bangladesh's population of 150 million is currently growing at ca 2 million a year: i.e., it could grow by 20 million in the next 10 years. That will generate much greater pressure on the country's land and water resources and its economy than will a slowly-rising sea-level. The country's agricultural land is already fully developed; in fact, considerable areas of valuable farmland are being lost to expansion of settlements and infrastructure each year (Brammer, 2010). Priority attention therefore needs to be paid to addressing current development and environmental problems: i.e., intensifying agricultural production; expanding economic activities outside agriculture; reducing exposure to existing levels of drought, floods and cyclones; supplementing dry-season flow in south-western rivers; and minimising impacts of arsenic-contaminated groundwater used for drinking and irrigation in large parts of the country (Ravenscroft et al., 2009). Rates of sea-level rise may increase and demand more urgent attention later in the 21st century, but Bangladesh faces serious problems now that need urgent attention if the country is to sustain its ability to feed, support and safeguard the livelihoods of its population in the short and medium terms.

However, several of the measures for mitigating the impacts of a rising sea-level described above are also needed to address current environmental and development problems. Most urgent of these is the need for measures to halt – and, if possible, reverse – the growing problem of salt-water intrusion in the south-west of Bangladesh. Water taken from rivers and groundwater for domestic, industrial or irrigation use anywhere in the Ganges and Brahmaputra catchment areas – inside as well as outside Bangladesh – decreases dry-season flow to the coastal zone; and it must be expected that increasing withdrawal of water in upper India in future decades will continue to decrease dry-season flow in the Ganges river before it reaches Bangladesh. That means that nation-wide measures are needed now to use water resources more efficiently, especially for irrigation, which would also be beneficial in arsenic-contaminated areas (Brammer, 2009). There is a present need, too, to test and introduce mitigation measures 2–8 described above as a means to increase agricultural production and to safeguard lives and livelihoods against current environmental hazards in relevant coastal and near-coastal regions.

In relation to sea-level rise, the most important early measure required is to start making more detailed assessments of the current physical, economic and human geography of the different physiographic regions and subregions within and adjoining the coastal zone in order to provide a comprehensive factual basis for planning current and future development. Existing institutions for monitoring tide levels, river flow, soil and water salinity, land levels and land use need to be strengthened. Field surveys will be needed to supplement existing information (some of which, like soil surveys carried out 50 years ago, will need to be updated); and interpretations of satellite images must be supported by adequate ground truthing. Such surveys will need to be followed by relevant studies to identify, test and cost appropriate intervention measures for individual areas, including institutional and political measures that might be needed to implement and support identified measures (Brammer, 2010). Budgets and time-frames for implementation in different areas will then need to be drawn up. Patently, it will be essential to engage local people in such studies and decisions in order both to harness their local environmental knowledge and to gain their support for implementing and supporting changes that are considered necessary in both their own and the national interest. The geographical diversity and complexity of Bangladesh's coastal zone and the multidisciplinary nature of many of the mitigation measures identified suggest that a comprehensive Integrated Coastal Zone Management Plan is needed, along the lines of the Dutch delta management plan, with appropriate staffing to prepare, operate and oversee it[5].

As was indicated earlier, many of the measures described above are needed regardless of a rising sea-level with global warming. So are several similar land and water management and institutional measures in other parts of the country to feed and employ the burgeoning population. Future sea-level rise – and climate change, also reviewed in Brammer (in press) – merely add urgency to the existing need for a national plan to implement relevant measures to safeguard, maintain and accelerate economic and social development in the country in pace with its growing population and its exposure to existing environmental hazards (Brammer, 2010). The range of studies needed in order to formulate such an integrated development plan in Bangladesh – the country in which intervention to meet current and future development needs is perhaps most urgently required – could provide a model for such planning in other countries with low-lying coastal areas.

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[5] Ideally, a comprehensive regional water management plan for the Ganges-Brahmaputra-Meghna catchment area is needed. However, to-date, India has not been prepared to support such a plan or to share hydrological data with Bangladesh, and Bangladesh has needed to prepare flood protection plans independently Brammer (2004).

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